AD________________

Award Number:
W81XWH-08-1-0186

TITLE:
Fabrication and Testing of a Blast Concussion Burst Sensor

PRINCIPAL INVESTIGATOR:
John A. Judge, Ph.D., PI
Scott A. Mathews, Ph.D., co-PI

CONTRACTING ORGANIZATION:
The Catholic University of America
Washington, DC 20064

REPORT DATE:
June 2010

TYPE OF REPORT:
Final

PREPARED FOR: U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012

DISTRIBUTION STATEMENT:

X Approved for public release; distribution unlimited

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
01-06-2010

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
1 June 2008 – 31 May 2010

4. TITLE AND SUBTITLE
Fabrication and Testing of a Blast Concussion Burst Sensor

5a. CONTRACT NUMBER

5b. GRANT NUMBER
W81XWH-08-1-0186

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
John A. Judge, Ph.D.
Scott A. Mathews, Ph.D.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
The Catholic University of America
Washington, DC 20064

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This project entails the design of passive, wearable sensors that provide an immediate and clear indication of the severity of exposure to explosive blasts, allowing soldiers with potential brain or other injuries to seek medical attention, and providing basic information about the blast to medical personnel. It focuses on development of burst membrane sensors, where the high pressure from an incident explosive shock wave ruptures a membrane sealing a reservoir containing an indicator dye. We created an experimental facility for testing prototype designs, developed appropriate explosive charges to simulate explosions capable of causing traumatic brain injury, and undertook several iterations of design and testing to achieve a suitable final prototype design. This design consists of a 0.15 mm thick glass membrane suspended over a 1/4-inch diameter reservoir well, scribed with a circular pattern slightly smaller than the well diameter. The result is simple to fabricate and assemble and ruptures at predictable pressure thresholds that are a function of the depth to which the glass is scribed.

15. SUBJECT TERMS
explosion, blast, traumatic brain injury, sensor, burst membrane

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			USAMRMC
U	U	U	UU	17	**19b. TELEPHONE NUMBER** *(include area code)*

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

Table of Contents

INTRODUCTION

This project entails the design and testing of passive, wearable sensors for military personnel that will provide an indication of the severity of exposure to explosive blasts, in an easily decipherable manner immediately following exposure. This will allow soldiers that may have traumatic brain injury (or other injury) that is not immediately apparent to seek medical attention, and also provide some basic information about the blast to medical personnel treating such soldiers. The devices developed in this project are burst membrane sensors, in which the incident shock wave from a nearby explosion imparts high pressure levels on precisely machined membranes sealing reservoirs containing indicators such as various colors of dye. Each membrane ruptures when exposed to pressure above a different threshold, so that the color of the dye released by the device becomes an indication of the severity of the blast. The goal is a completely passive sensor that is low cost, does not require electrical power, and that provides an indication of blast severity that is immediately apparent to personnel without the need for additional diagnostic equipment or technical training.

The scope of the research described here includes designing, fabricating, and testing such sensors. The primary objective is a design that provides consistent, repeatable performance at appropriate pressure thresholds. The research also includes some consideration of secondary issues including packaging and mounting such devices.

BODY

The project plan was divided into 6 tasks grouped into three phases: (I) Materials Characterization, (II) Membrane Design, and (III) Sensor Testing. A detailed description of the work carried out on each task, and the associated research findings, follows.

Phase I: Tasks 1 and 2 (Materials Characterization)

As described in the first annual report for this project, a number of materials were explored for use as burst membranes, including glass, various metals, and plastics. Glass was selected as the material of choice due to ease of obtaining specimens of uniform thickness and appropriate size, ease in handling during the fabrication process, transparency (unnecessary for a finished product but advantageous for diagnostic purposes during testing), suitability for laser micromachining, and brittle failure (lack of plastic deformation). Glass microscope cover slips were used due to their commercial availability in standard sizes and thicknesses. Several thicknesses of such cover slips were evaluated, including #0, #1, #1.5, and #2; the final design is a membrane machined from a 22 mm square #1 cover slip, with a typical thickness of 0.155 mm. As described below, a laser micromachining system was used to scribe patterns into this glass at depths ranging up to 0.015 mm (~10% of the glass thickness), with the depth and scribe pattern determining the pressure threshold for rupture. Thinner glass was found to be susceptible to breakage at undesirably low pressure thresholds even in the absence of a scribed pattern. Thicker glass required significantly deeper scribed patterns for rupture at desired pressure thresholds. As the desired cut depth increases, an increasing number of passes with the cutting laser are required, and cut depth uniformity decreases. In addition, thicker glass required a greater *relative* cut depth (depth as a fraction of overall thickness) leading to increasing difficulty in obtaining precise and repeatable results.

Phases II and III: Tasks 3, 4, and 5 (Membrane Design and Sensor Testing)

The basic concept for the burst membrane prototypes developed under this award is a sequence of reservoirs of various colored liquids sealed by membranes that are engineered to rupture when subject to explosive shock waves above various pressure thresholds. The pressure threshold for injury to various body tissues is a function of the duration of the overpressure [1] (see Fig. 1). In turn, both the duration and peak overpressure level depend on the effective yield of the explosive and the distance from the explosion.

As described in the first annual report for this project, we focused on a pressure range between 100 and 1000 kPa peak overpressure. For 1 millisecond duration exposure, this pressure range spans injuries from possible eardrum rupture at the low end to 1% likelihood of lethality at the high end. Greater duration exposure to the same pressures increases the likelihood and severity of injury. The region of interest (for the application of providing an indicator for potential brain injury due to soldiers exposed to typical roadside bombs and other improvised explosive devices) is indicated by the gray rectangle in Fig. 1, with overpressure durations between 1 and 20 msec. The shock wave from an explosion with yield equivalent to 1 lb TNT has an overpressure duration between 1 and 2 msec (depending on distance from the explosion) [2], and the overpressure duration increases according to the cube root of explosive yield, resulting in a duration of 10 to 20 msec from a 1000 lb TNT equivalent explosion.

Experimental facility and test explosives

The experimental system developed during this project in order to subject prototype membranes to controlled blasts was described in detail in the first annual report. A system schematic and photograph are included as Fig. 2 and Fig. 3, respectively. An explosive charge is detonated at one end (the left end in Figs. 2 and 3) of the blast tube. The time lag in the arrival of the shock front at the two pressure sensors along the length of the tube allows the speed of the shock wave to be calculated, while the third pressure sensor, at the same location as the burst membranes being tested, provides a measurement of the overpressure amplitude experienced by the membranes.

The custom explosive charge developed for this test apparatus were also described in detail in the first annual report. We used 1.0 grams of smokeless black powder and a model-rocket igniter inside a steel vessel consisting of a 1 inch threaded nipple and two end-caps. A photograph of a typical explosive charge and its constituent parts is included as Fig. 4. The end cap opposite the igniter leads (the right end in Fig. 4) is milled to a precisely controlled thickness, ensuring that the vessel failure always occurs at the same end of the charge, and controlling the yield of the explosion through the thickness of steel at the failure point. A variety of end-cap thicknesses, from 0.025 to 0.060 inches (0.6 to 1.5 mm) were used in an attempt to provide various peak overpressures to the test specimens, however, more controlled variations in membrane pressure exposure were obtained by using the same end-cap thickness and varying the standoff distance of the test specimens from the end of the tube. Once the shock wave leaves the blast tube, spherical spreading reduces the peak overpressure rapidly with increasing distance. We used distances ranging for 1 to 9 inches (25 to 229 mm) to expose the test specimens to pressures in the desired range; in all cases, the membranes faced directly into the incident explosive shock wave.

Typical data from the pressure sensors in shown in Fig. 5. For this particular explosion, the time lag between sensors 1 and 2 indicates a speed of 650 m/s (about Mach 1.9), and the pressure decay after peak pressure has a time constant of approximately 1 msec (this is taken to be the overpressure duration). The peak pressure level is approximately 400 kPa and 250 kPa at sensors 1 and 2, respectively, however, sensor 3, like the prototype membranes, is oriented to face the explosive shock front head-on, and thus experiences a large peak overpressure of approximately 1100 kPa (the interaction of incident and reflected supersonic waves causes peak overpressures as much as eight times higher than the incident static pressure level, depending on the wave speed [2]). This particular result (overpressure of 1100 kPa and duration of 1 msec) places the particular blast in question just above the top left corner of the region of interest shown in Fig. 1.

All of the data collected as part of this project was on explosions with peak overpressure duration of roughly the same duration; significantly larger explosive charges (and thus a significantly larger and stronger test facility) would be necessary to develop longer duration exposure. Because the glass membrane thickness is small (0.155 mm) with respect to the length scale of the shock wave (approximately 500-600 mm), it is expected that the membranes would rupture at the same pressure thresholds even if the pressure duration were increased to the upper end of the range of interest. High-speed video of the membrane rupture (see below) indicates fracture of the glass occurs on a time scale of approximately 10 microseconds, several orders of magnitude faster than the duration of overpressure exposure.

The various tests carried out as part of this project exposed the test specimens to pressures between 125 kPa and 1100 kPa (the result described above and shown in Fig. 5 is at the high end). As stated previously, variations in pressure were obtained by varying the thickness of the machined end-cap of the explosive charge as well as the distance of the test specimens from the end of the blast tube.

Specimen mounting

As described in the first annual report, each prototype test specimen consists of a membrane fixed over a circular reservoir in a plastic base plate, intended to hold a colored liquid that will spill from the device only if the membrane ruptures. Based on early tests with a variety of well diameters, 0.250 inch diameter wells were selected as most suitable given the fabrication and assembly constraints, and the desirability of a device large enough for easy observation of test results "by eye." Smaller well diameters may be appropriate for blast sensors deployed to the field, however, it must be noted that the stress in the membrane (when subject to any given overpressure) scales as diameter squared [3], so smaller wells would require the glass membrane to be weakened by deeper scribe patterns.

A number of solutions for mounting membranes over the wells were considered. Various adhesives were considered in an attempt to provide a waterproof seal while maintaining ease of fabrication and consistent results. Norland optical adhesive #68 (a waterproof, UV-cure epoxy) was found to provide a proper seal, and fabrication was simplified by the fact that the adhesive does not set until exposed to UV light. However, difficulty in producing samples with a sufficiently uniform amount of adhesive (and uniform coverage of the glass-plastic interface) caused us to favor a mechanical mounting system during testing, in which the adhesive was eliminated and the glass was held in place against the substrate by a cover plate and screws. We expect that dedicated manufacturing facilities would be able to resolve the inconsistencies we faced when using adhesive, and that adhesive would be a preferred method of mounting burst membrane sensors deployed to the field.

Membrane Design and Fabrication

Prototype burst membranes were fabricated by scribing a pattern on the 0.155 mm thick glass microscope cover slips using multiple passes of the beam of a 2 Watt 266 nm laser microfabrication system. A number of scribe patterns were considered before selecting a simple circular scribe pattern with a 0.22 inch (5.6 mm) diameter (slightly smaller than the 0.25 inch diameter of the well in the substrate). A uniform pressure load on the surface of a circular membrane results in shear stress, hoop (circumferential) stress, and radial stress than all vary across the thickness and with radial location [3]. The radial stress is highest at the top and bottom surfaces of the membrane and at maximum radius, and, for reasonable dimensions, is approximately two orders of magnitude greater than the hoop stress and shear stress, and is thus the stress responsible for fracture. Scribing a circle on one face of the glass through this region of maximum radial stress weakens the glass in two ways. The decrease in glass thickness increases the stress corresponding to a given load (the radial stress is proportional to the reciprocal of thickness to the third power, so a 10% decrease in thickness would result in $(0.9)^{-3} \approx 1.37$ or a 37% increase in stress for a given load). Furthermore, the presence of the scribe results in a local stress concentration, i.e., stresses are significantly greater in the vicinity of the scribe that they would be in a uniform glass sheet. Once a crack forms along the scribe, it rapidly propagates through the glass membrane thickness and around the circumference of the scribe, allowing the disk of glass over the well to break off (the disk typically shatters in the process).

Figure 6 shows a photograph of a glass membrane scribed with this pattern, as well as a photograph of a membrane that has ruptured due to explosive shock loading. Figure 7 shows three frames from a high-speed video taken of a membrane rupturing. The video was recorded at 220,000 frames per second; the three frames shown are consecutive frames approximately 4.5 microseconds apart. Note that the crack at the scribe pattern takes less than one frame to form and propagate around the circumference. By the third frame, the central disk has begun to move into the well, shattering as it does so.

The depth of the scribed pattern (and thus the pressure threshold for rupture of the glass membrane) is controlled by the number of passes with the laser. Initially, each pass of the 2 Watt 266 nm pulsed laser removes approximately 1 micron of glass. As further passes are made, cutting efficiency declines. The table at right shows the approximate scribe depth for various numbers of laser passes, as well as the percentage removed from the nominal thickness of a size #1 glass cover slip.

Number of laser passes	Approx. Depth (μm)	% of thickness of 153 μm glass (#1 cover slip)
3	3	1.9%
5	5	3.2%
7	7	4.5%
11	10	6.5%
15	12	7.7%
20	15	9.7%

The scribe depth was characterized using an optical profilometer. Note that, although the laser vaporized most of the glass removed, there is some buildup of glass (due to melting and resolidification) on either side of the groove. Figure 8 shows typical optical profilometry data (in this case, for glass scribed 3 times, to a depth of approximately 3 μm). The width of the groove is approximately 25 μm at the top surface (tapering narrower with depth) and there is approximately 0.5 μm extra glass built up on either side of the groove.

Sources of Uncertainty

Each stage of the fabrication and testing procedure is subject to a certain degree of imprecision or uncertainty. In some cases, this can be measured and accounted for, however, in other cases it leads to unavoidable imprecision in the measured results (described below).

A described above, the magnitude of overpressure incident on the test specimens from the test explosions was controlled by varying both the thickness of the steel end-cap of the explosive charge and the distance of the test specimen from the end of the blast tube. The steel end-caps were machined to specific thicknesses in the range 0.025 to 0.060 inches (0.6 to 1.5 mm), measured to a tolerance of ±0.0005 inches (±13 μm). However, even for nominally identical end-cap thicknesses and identical sample placement, there was considerable variation (on the order of 10%) in speed and amplitude of the shock wave from one explosion to the next. This variation was accounted for in the test results due to the fact that the precise speed of each shock wave was measured as it traveled along the blast tube, and the amplitude of the overpressure at the test specimen location was measured during each test. However, there is some additional unavoidable uncertainty in the overpressure amplitude incident on each individual test specimen, due to the fact that pressure sensor #3, while located the same distance from the blast tube as each test specimen, is a small lateral distance (approximately 1.5 to 2.1 inches) away from each specimen. The blast tube was designed to give the shock wave sufficient travel distance to fully develop, with the intent of providing a uniform wave across the tube diameter by the end of the tube. Nevertheless, there is some spatial variation in overpressure amplitude across the fixture holding the test specimens and third pressure sensor. By temporarily mounting all three pressure sensors in the test fixture and thereby simultaneously measuring the pressure at multiple lateral locations, the variation in pressure was found to be less than 10% when the test fixture was placed directly at the end of the blast tube.

According to the microscope cover slip standard thickness conventions, the range of acceptable thicknesses for a #1 glass cover slip is 130 to 160 μm. The particular cover slips used for this project were all purchased from a single vendor, and were measured using a micrometer screw gauge and found to have thickness of 155±3 μm. The profilometer used to measure scribe depth is extremely precise, but measurements at different locations on the same sample as well as comparison of measurements from different samples revealed variation in cut depth on the order of 5%. The largest source of variation from one test specimen to the next was likely due to mounting: variations in the clamping force holding the glass in place against the substrate and the possible presence of small contaminants (such as dust particles) between the two layers give rise to pre-stresses in the glass membrane which can affect the overpressure at which rupture occurs, and which are difficult to quantify.

Test results

Several hundred test specimens were evaluated over the course of this project, including over 200 membranes based on the final design (a circular scribe with 0.22 inch diameter in 155 μm thick glass over a 0.25 inch diameter well). Table 1 below summarizes the results. Membranes scribed with a circular pattern only 3 μm deep did not rupture even when exposed to 1 MPa peak overpressure. However, only a small increase in cut depth, to 5 μm, was required to lower the pressure threshold for rupture significantly. When exposed to pressures above 800 kPa, the majority of membranes scribed to 5 μm ruptured. Membranes scribed to a depth of 7 μm were more likely to rupture than not at any pressure above 400 kPa and invariably ruptured at pressures above 800 kPa. Membranes scribed to even greater depths ruptured a progressively lower pressure thresholds.

Table 1: Summary of Test Results

(Percentage of membranes rupturing as a function of peak overpressure and scribe pattern depth)

Pressure range (kPa)	3 μm	5 μm	7 μm	10+ μm
900-1000	0%	80%	100%	100%
800-999	0%	56%	100%	100%
600-799	0%	30%	90%	100%
400-599		25%	69%	100%
200-399		17%	10%	18%
below 200		0%	0%	0%

The statistics presented in the summary table are based on varying number of test specimens (see Appendix). The percentage of tested membranes that ruptured can be seen as an estimate of the likelihood that a given membrane will rupture when exposed to a particular peak overpressure. The accuracy of this estimate depends on the total number of samples tested; Table 2 below summarizes the 95% confidence intervals for the likelihood of breakage of membranes in each category, for those categories in which some but not all membranes ruptured (these intervals were calculated using the method introduced by Wilson [4], which has been shown to be more accurate than the more common Wald interval, particularly for small sample sizes [5]). Note that the width of these confidence intervals is inversely proportional to the square root of the number of samples tested, so obtaining precise estimates of the likelihood of breakage in each category would require a significantly larger number of tests. In addition to refining these estimates, further testing (of a much larger number of samples) could allow pressure to be divided into narrower ranges, giving more precise information about the pressure thresholds for possible failure and definite failure of each membrane type. Note that the ranges used in the above table are each 200 kPa wide except for the highest ranges, which are 100 kPa wide each, to better show the decrease in rupture rate of the 5 μm deep scribed membranes as pressure decreases. The results above also indicate that it may be desirable to consider membranes with finer gradations in scribe depth. For instance, although 3 μm deep scribes never lead to rupture at pressures below 1000 kPa, a 4 μm deep scribe could potentially lead to rupture at pressures approaching 1000 kPa but consistently remain intact at lower pressures (at which membranes scribed 5 μm deep sometimes do rupture).

Table 2: Estimates of likelihood of breakage (95% confidence intervals)

(Results are shown only for categories in which some but not all membranes ruptured)

Pressure range (kPa)	3 μm	5 μm	7 μm	10+ μm
900-1000		49-94%		
800-999		27-81%		
600-799		11-60%	60-98%	
400-599		9-53%	42-87%	
200-399		6-39%	3-30%	8-34%
below 200				

The results demonstrate a significant spread in between the pressure at which rupture is *possible* and the pressure at which rupture is *certain*. To some degree, this limits the utility of a single sensor (for example, rupture of a single membrane scribed 5 μm deep only indicates that blast exposure *may* have been dangerously high, since rupture of such membranes does occasionally occur at pressures as low as 200 kPa). The gap between the thresholds for possible rupture and certain rupture may be due to various uncertainties in the experiment, described above. It is possible that sufficiently precise fabrication and assembly of burst membrane sensors could reduce this gap. It is worth noting that, even if it is impossible or impractical to fabricate a sensor that always fails above a particular pressure threshold and never fails below the *same* threshold, there is still considerable value in the information provided by a sensor that possesses an intermediate pressure range where rupture is possible but not certain, and still greater informative value provided by a series of such sensors designed for different rupture thresholds and exposed simultaneously to the same blast. For instance, while rupture of a membrane scribed 5μm deep would by itself indicate likelihood of high pressure exposure, the failure to rupture of an adjacent 7 μm scribed membrane would rule out pressures above 800 kPa, while rupture of such a 7 μm scribed membrane would indicate increased likelihood that the pressure was not below 400 kPa.

KEY RESEARCH ACCOMPLISHMENTS

- Designed and constructed a blast tube test apparatus, in which an explosion is triggered at one end, the resulting shock wave is measured and characterized as it travels along the tube, and prototype test specimens can be placed in the path of the shock wave at the far end of the tube.
- Designed custom explosive charges that can be machined in order to provide desired levels of shock overpressure in the range encompassing minor injury to fatality in humans.
- Tested several generations of burst membrane prototype designs and selected, as a final design, a circular scribe pattern (of varying depth depending on desired rupture threshold) of 0.22 inch (5.6 mm) diameter in 150 μm thick glass, suspended over a 0.25 inch (6.4 mm) diameter well in a plastic substrate.
- Characterized the pressure thresholds at which this design ruptures for various scribe depths, by experimentally observing the frequency of rupture when exposed to various explosive shock overpressures.

REPORTABLE OUTCOMES

To date, no journal articles were published or conference presentations given relating to this project. The investigators plan to prepare a journal article in the near future to publish their results. One graduate student, Mr. Patrick Fry, was supported using funds from this award during the past year. Mr. Fry obtained his Master of Science in Engineering degree in May 2009.

CONCLUSION

The prototype burst membrane sensors developed during this project demonstrate the feasibility of a completely passive, non-powered sensor that can provide an indication of explosive blast exposure severity. With proper manufacturing facilities, and leveraging economies of scale, such sensors could be produced at extremely low cost, allowing them to be deployed to all appropriate military personnel (anyone operating in a location at risk of exposure to explosive blasts). Such sensors can provide an easily recognizable indication of exposure to blasts above various pressure thresholds (for example, releasing various colors of dye), allowing anyone exposed to intermediate level blasts (where injuries are likely/possible but are not immediately apparent) to seek appropriate medical attention. Furthermore, by allowing medial personnel to correlate the maximum pressure exposure to the type and severity of injury sustained, such sensors may serve to enhance the understanding of the interaction between supersonic shock waves and various human tissues.

While successfully demonstrating proof-of-concept and providing a workable design for such sensors, this project has also shown a number of issues that must be addressed by anyone attempting large-scale production of such sensors. In particular, the results shown above indicate that the pressure threshold at which rupture occurs in highly sensitive to scribe depth, and that, for any particular scribe depth, there appears to a significant range of pressures over which rupture is possible but not assured. The first issue can be addressed by using a sufficiently precise and repeatable technique for scribing the glass membranes. The second issue may be due to remaining unresolved variation among nominally identical membranes, which could be resolved with sufficiently precise fabrication and assembly. The use of multiple, adjacent burst membrane sensors, each with different rupture thresholds, allows more accurate estimation of blast pressure level exposure.

The results of this academic study indicate that passive burst membrane sensors are a promising technology for quantifying blast exposure. Further development of this concept should include an industrial or government partner capable of precisely mass-producing such membranes, and should feature testing using actual high-explosive detonations more typical of what would be experienced in the field. A larger-scale testing of such sensors would increase the precision of the pressure threshold estimates for various scribe depths, and allow further refinement of the sensor design. Before eventual field-testing and subsequent deployment of this technology, a number of issues must be resolved, including where and how such sensors would be mounted on a soldier's helmet or uniform, and how the burst membranes can be enclosed or shielded to prevent unintended breakage in non-explosive situations while retaining their sensitivity to explosive shock waves.

REFERENCES

[1] Bowen, T.E. and Bellamy, R.F., eds., *Emergency War Surgery*, United States Government Printing Office, Washington, DC, 1988.

[2] Kinney, G. F., *Explosive Shocks in Air*, Macmillan, New York, 1962.

[3] Timoshenko, S.P., Woinowsky-Krieger, S., *Theory of Plates and Shells (2nd Ed.)*. McGraw Hill, New York, 1959.

[4] Wilson, E. B., "Probable Inference, the Law of Succession, and Statistical Inference," *Journal of the American Statistical Association*, Vol. 22, pp. 209-212, 1927.

[5] Brown, L. D., Cai, T. T., and DasGupta, A., "Interval Estimation for a Binomial Population," *Statistical Science*, Vol. 16 (2), pp. 101-133, 2001.

APPENDIX

Throughout the course of the project, tests were conducted on numerous iterations of prototype designs. Once the final design was selected, a total of 276 membranes, of various scribe depths, were tested, subject to a variety of peak overpressure amplitudes. Table 3 lists the number of membranes tested in each category. The results summarized in Table 1 and the rupture likelihoods estimated in Table 2 are calculated based on the fraction of each of these samples that ruptured when exposed to the relevant overpressure shock wave.

Table 3: Number of samples of final membrane design tested in each category

(Total number tested = 276)

Pressure range (kPa)	3 μm	5 μm	7 μm	10+ μm
900-1000	10	10	10	18
800-999	8	9	7	12
600-799	18	10	10	14
400-599		12	13	23
200-399		18	20	34
below 200		6	6	10

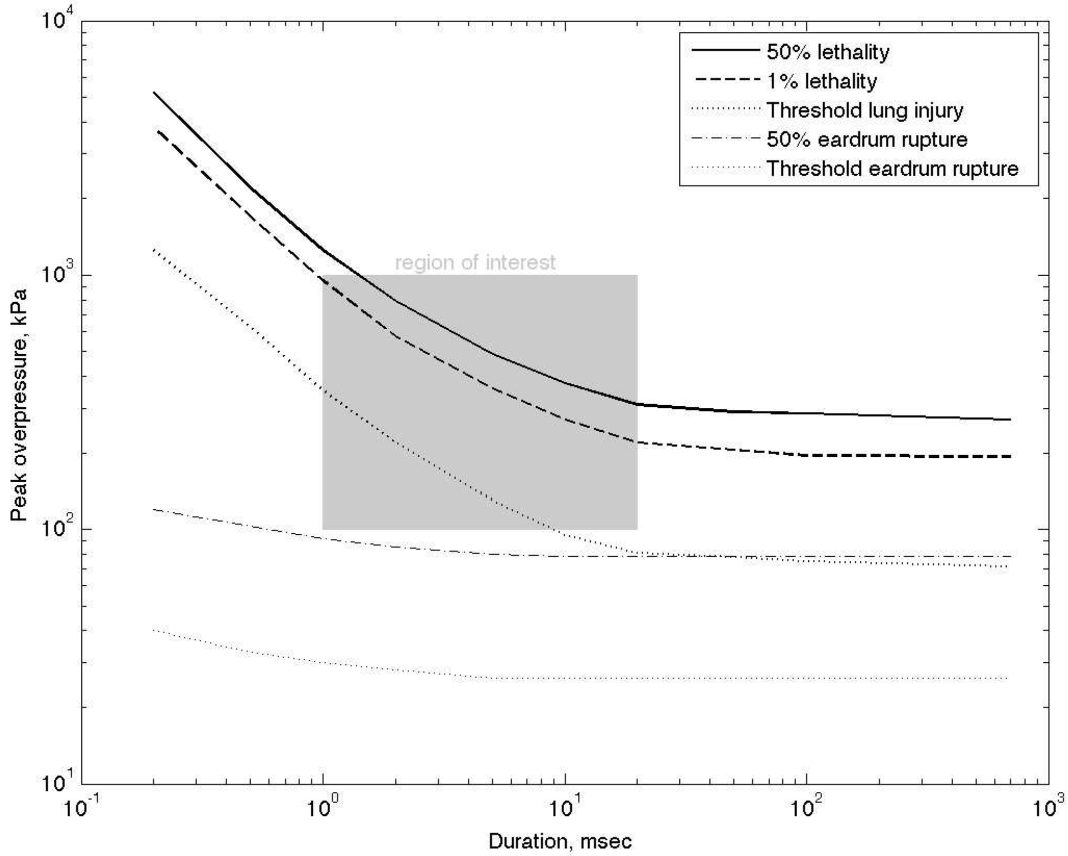


Figure 1: Thresholds of injuries as a function of blast duration and overpressure [1]. The design goal is membranes that burst at specific pressure levels between 100 and 1000 kPa when subjected to blasts with overpressure durations between 1 and 20 msec.

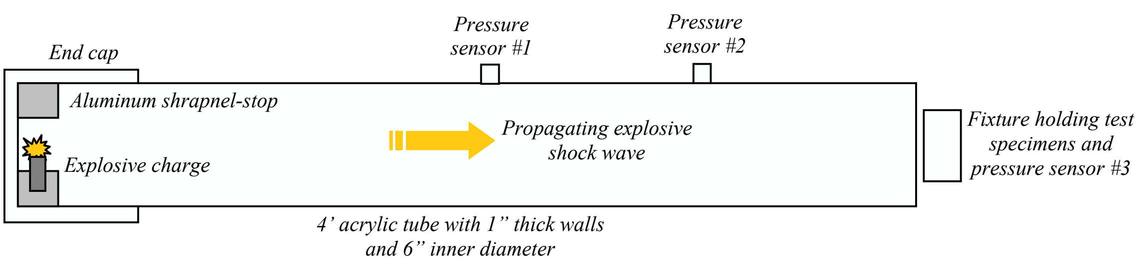


Figure 2: Schematic of blast tube test apparatus

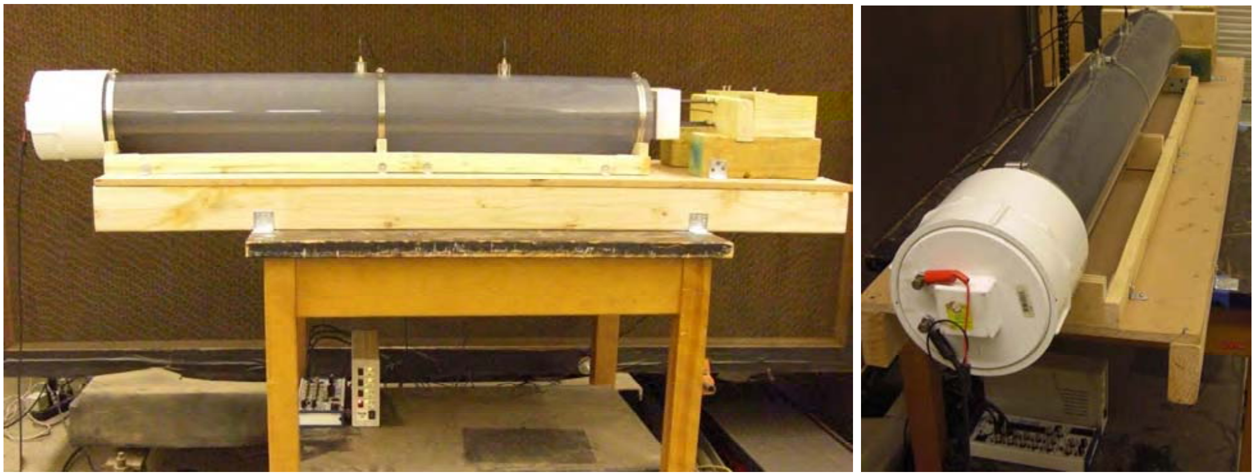


Figure 3: Photographs of blast tube for testing burst membrane prototypes. Side view (*left*) and view from end containing explosive charge (*right*).

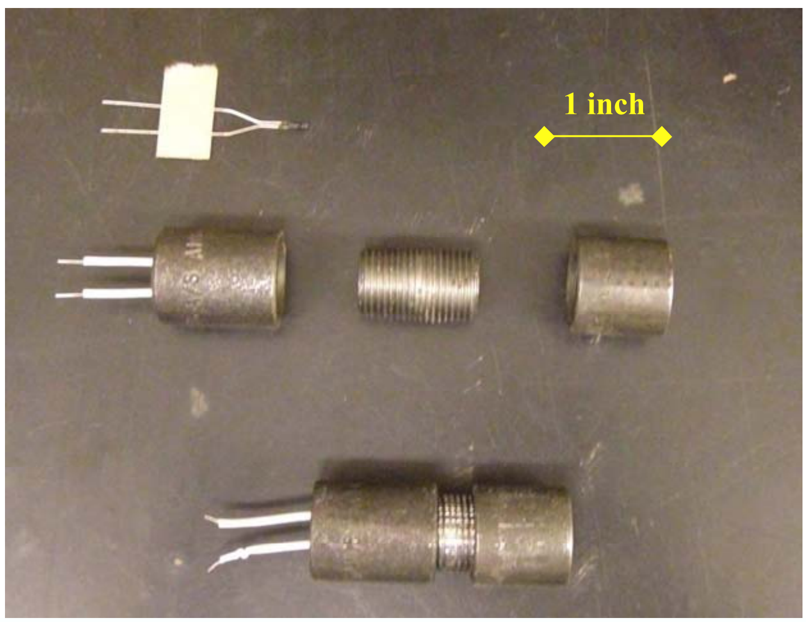


Figure 4: Components of an explosive charge, including igniter (*top left*), steel base cap with igniter epoxied inside and wires protruding (*center left*), 1 inch steel nipple (*center*), and top cap with end milled to a precise thickness to control the peak overpressure (*center right*). An assembled charge, containing 1.0 grams of smokeless black powder, is shown at *bottom*.

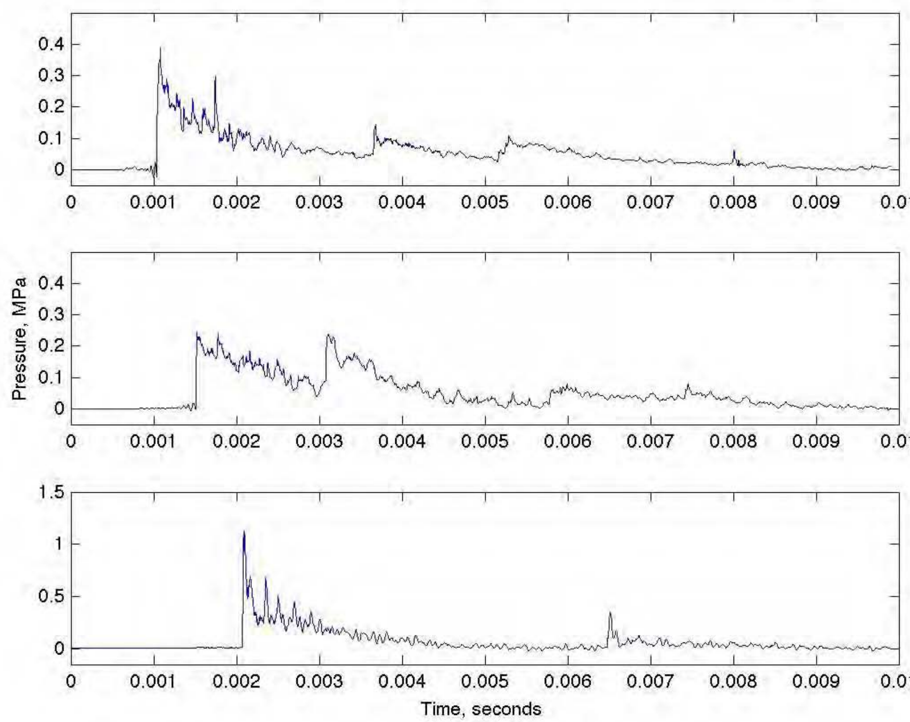
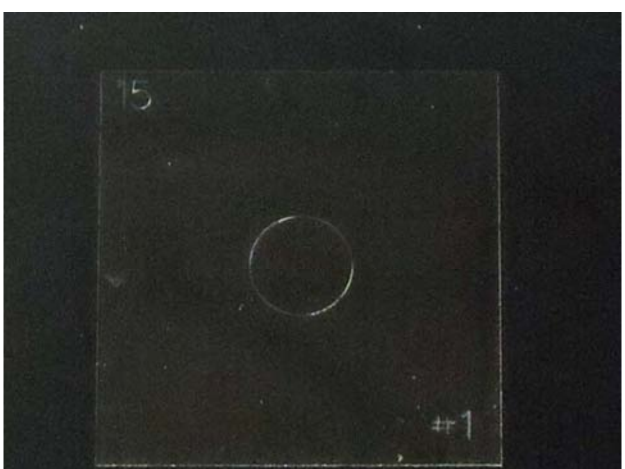


Figure 5: Pressure sensor records for a typical shock wave during prototype testing. Sensor #1 (*top*) is at mid-tube, sensor #2 (*center*) is 12 inches further along the tube, and sensor #3 (*bottom*) is at the same distance as the test specimens, at the open end of the tube furthest from the explosive charge. Note that, in addition to the initial shock front, the reflection from the test fixture is visible in the sensor #2 data (just after 3 msec) and sensor #1 data (around 3.7 msec). Secondary and tertiary reflections are also visible.



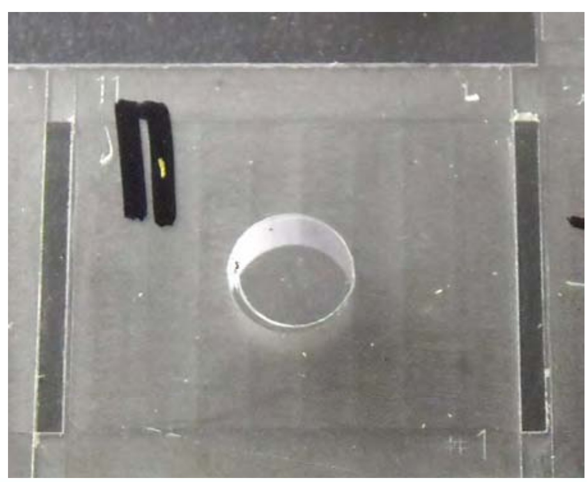


Figure 6: Photographs of scribed glass membrane (*left*) and ruptured membrane of a test specimen after testing (*right*). In addition to the circular scribe pattern, each glass cover slip is scribed in the top left corner with the number of laser passes used to scribe the pattern, and in the bottom right corner with the cover slip size.

Figure 7: Frames from high-speed video of membrane rupturing. *Left:* immediately prior to arrival of shock front (circular scribed pattern is faintly visible). *Center:* immediately after arrival of shock front: glass has cracked around circular scribe pattern. *Right:* shattering of circular disk as it begins to move into well in substrate. Individual frames are approximately 4.5 microseconds apart. Note that the video was taken from an angle (the membranes face directly into the blast tube) resulting in the oval appearance of the circular well and membrane.

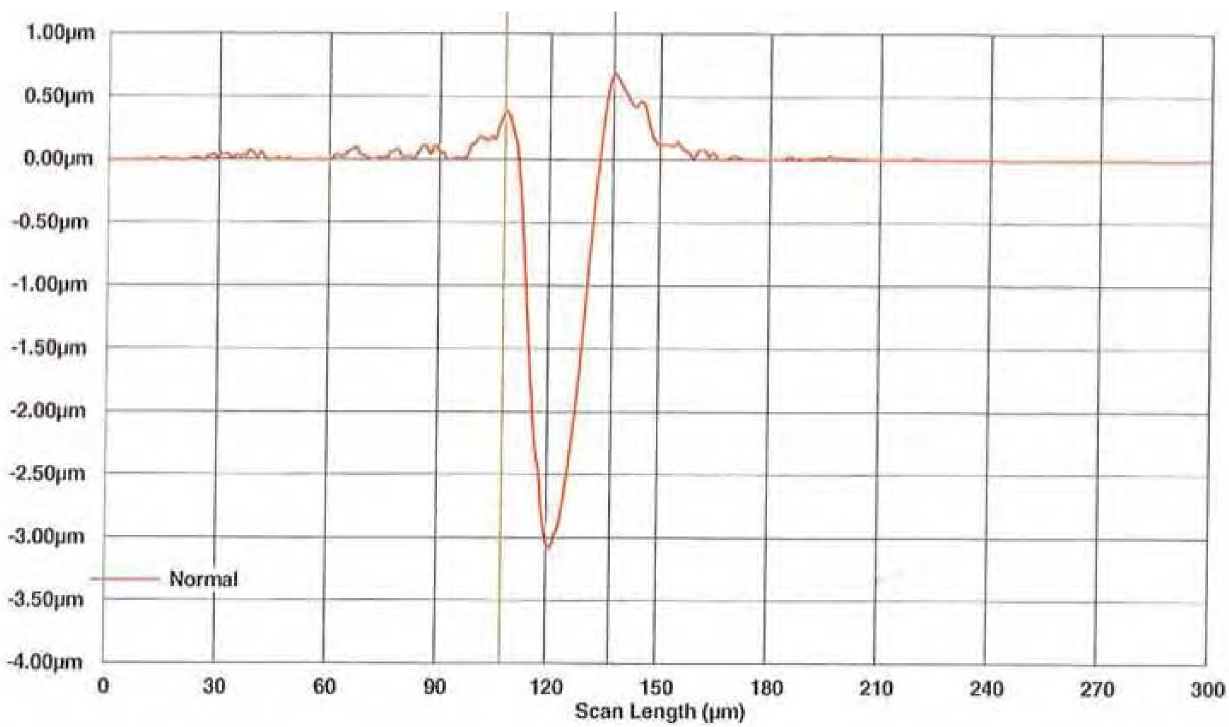


Figure 8: Typical optical profilometry data showing the cross-sectional profile of a groove scribed into the surface of a glass cover slip. In this case, the laser made three passes, resulting in a groove approximately 3 µm deep and 25 µm wide, with as much as 0.5 µm glass buildup along the edges of the groove.